

Parsec-Scale Behavior of Blazars during High Gamma-Ray States

S. Jorstad^{1,2}, A. Marscher¹, I. Agudo^{1,3}, B. Harrison¹

1. Boston U., 725 Commonwealth Ave., Boston MA, 02215, USA

2. St.Petersburg State U., Universitetskii pr. 28,

Petrodvorets, 198504, St. Petersburg, Russia and

3. Instituto de Astrofísica de Andalucia, CSIC, Apartado 3004, 18080, Granada, Spain

We compare the γ -ray light curves of the blazars, constructed with data provided by the Fermi Large Area Telescope, with flux and polarization variations in the VLBI core and bright superluminal knots obtained via monthly monitoring with the Very Long Baseline Array at 43 GHz. For all blazars in the sample that exhibit a high γ -ray state on time scales from several weeks to several months, an increase of the total flux in the mm-wave core is contemporaneous with the γ -ray activity (more than a third of the sample). Here we present the results for quasars with the most extreme γ -ray behavior (3C 454.3, 3C 273, 3C 279, 1222+216, and 1633+382). The sources show that in addition to the total flux intensity behavior, a maximum in the degree of polarization in the core or bright superluminal knot nearest to the core coincides with the time of a γ -ray peak to within the accuracy of the sampling of the radio data. These argue in favor of location of many of γ -ray outbursts in blazars outside of the broad line region, either in the vicinity or downstream of the mm-wave VLBI core.

I. INTRODUCTION

The unprecedentedly detailed γ -ray light curves provided by the Fermi Large Area Telescope (LAT) show that blazars exhibit long-lasting (several months) activity states characterized by several flares with γ -ray flux $>10^{-6}$ phot cm⁻² s⁻¹, each with duration of ~ 1 -15 days and variability timescale as short as ~ 1 hr, e.g., [1, 2, 4, 10]. Although there is no doubt that the presence of a relativistic jet and γ -ray emission are tightly connected, e.g., [8], the locations and mechanisms of the high energy origin are unclear and highly debated, e.g., [3, 11], with some evidence that different mechanisms and locations could be present even in a single source [10].

We perform total and polarized intensity imaging of the parsec-scale jets of a sample of 35 γ -ray blazars obtained monthly with the Very Long Baseline Array (VLBA) at 43 GHz [12] at ultra-high resolution (0.1 milliarcseconds), starting in Summer 2008 when the Fermi Gamma-Ray Space Telescope began to operate. We also undertake short campaigns of 2-week duration 2 times per year involving 3 VLBA epochs at 43 GHz for each campaign. The VLBA observations determine the flux and polarization of the millimeter-wave core and other components of the jet, as well as the kinematics and evolution of bright superluminal knots. We compare the γ -ray light curves of the blazars, constructed with data provided by the Fermi LAT, with flux and polarization variations in the VLBI core and bright superluminal knots. Here we present results of the comparison for the quasars 3C 273, 3C 279, 3C 454.3, 1222+216, and 1633+382, which underwent exceptionally high γ -ray outbursts during the last three years.

II. DATA REDUCTION

We processed the VLBA data and created images in a manner identical to that described in [5]. We modelled the images in terms of a small number of components with circular Gaussian brightness distributions and determined polarization parameters of components using an IDL program that calculates the mean values within an area equal to that of the size established by the model fit. Figures 1-3 show the total and polarized intensity images of 3C 273, 3C 279, 3C 454.3, 1222+216, and 1633+382 along with identifications of moving knots. The core is a presumably stationary feature located at one end of the jet. Figure 4 shows the γ -ray light curves, as well as the light curves of flux and degree of polarization of the VLBI core (light curves of the core and superluminal knots in the case of 3C 273). The γ -ray light curves were constructed with a bin size of one week (one day for 3C 454.3 and 3C 273 during the high γ -ray state) using the P6 photon and spacecraft data and *v9r18p6-fssc-20101108* version of Science Tools provided by FSSC.

III. DISCUSSION

In all 5 objects, which exhibit dramatic γ -ray activity during 2008-2010, we observe a simultaneous increase of total intensity and fractional polarization in the core at 43 GHz (7 mm) accompanied by the appearance of superluminal knots in the jet.

The quasar 3C 273: The light curve in Figure 4 shows a high γ -ray state of the quasar during 2009.6-2010.3 (JD: 2455050-2455300) featuring 5 prominent γ -ray peaks. We have identified 7 superluminal knots (disturbances) in the jet of 3C 273 within 2 mas of the core (Fig. 1 & 4), out of which 4 components (I2, I3, I4, and I5) appeared in the jet during the γ -ray

events. The apparent speeds of the components range from 7c to 12c. These four components were ejected within 1 yr (from 2009.5 to 2010.5), while the average rate of ejection of superluminal knots in 3C 273, e.g., in 1998-2001, is 0.7 knots per year [5]. This indicates a significant increase of activity in the parsec-scale jet contemporaneous with the γ -ray events. The fastest knot, I2 (12.0 ± 0.7 c), can be associated with the most prominent γ -ray peak, while the brightest knot, I4, had maximum flux coinciding with the last γ -ray peak.

The quasar 3C 279: In 3C 279 we observe two knots (Fig. 1), K2 & K3, whose appearance in the jet is accompanied by an increase of flux and fractional polarization of the core (Fig. 4). The knots have apparent speeds of 16.3 ± 2.0 c and 19.7 ± 2.0 c, respectively, and their time of passage through the mm-wave core coincides with the two most prominent events in the γ -ray light curve, Dec. 2008 - Apr. 2009 and in Autumn 2010 (Fig. 4).

The quasar 3C 454.3: In 3C 454.3 the γ -ray outburst in the end of 2009 had three prominent peaks (I, II, & III, Fig. 4). Peak I coincides within 2 ± 5 days with the passage of knot K09 through the core. The knot is very bright ($S_{max} = 17$ Jy) and moves with an apparent speed of 10.5 ± 0.3 c. Although the flux and degree of polarization in the core increase during the radio/ γ -ray events, the maximum polarization occurred on 19 May 2010, ~ 200 days after the start of the γ -ray activity and ejection of K09. Note that the position angle of polarization (EVPA) of the core and K09 are almost orthogonal (Fig. 1). The peak in polarization corresponds to the exit of the knot from the core region into the extended jet, which we associate with the last γ -ray event, III. Therefore, all three γ -ray flares occurred while K09 was passing through the core region. This gives a size of the core region of ~ 0.13 mas, equal to the sum of the sizes of the core (~ 0.06 mas) and K09 (~ 0.08 mas) obtained by the model fit from January to May 2010.

The quasar 1222+216: The γ -ray flux from 4C21.35 increased at the end of September 2009 and remained high until January 2011 (Fig. 4). The source was confidently detected at TeV energies on 17 June 2010 (ATel #2684). A very short time scale of γ -ray variability (~ 0.8 hr) was found during this period [4]. The source is strongly core dominated at 43 GHz. We see a doubling of the flux and a significant

increase of polarization in the core at 43 GHz during the high γ -ray state. A new superluminal knot, K1, moves down the jet at an apparent speed of 14.2 ± 0.4 c (Fig. 2), passing through the mm-wave core during the most prominent γ -ray peak (within the 1σ uncertainty in ejection time). We also find a statistically significant correlation between γ -ray and optical variations as well. In addition, the optical linear polarization increased from $<1\%$ to 6.5% during the high γ -ray state while the optical EVPA rotated by 200° [6]. This behavior has a similar pattern as reported previously during high-energy outbursts in BL Lac [9], PKS 1510-089 [10], and 3C 279 [1].

The quasar 1633+382: In 2009 September an increase in γ -ray emission by a factor of ~ 10 coincided with a gradual increase in the VLBI core flux of the quasar. A high γ -ray state persisted for ~ 1 yr and in early 2011 a new activity cycle started (Fig. 4). The VLBA images (Fig. 3) show moving knot K2, with an apparent speed of 7.5 ± 0.4 c, that passed through the core around 2-10 September 2009, coincident with the first peak of the 2009 γ -ray outburst. Comparison between the optical EVPA and that in the VLBI core supports the idea that in the quasar 1633+382 a high γ -ray state is connected with processes originating near the mm-VLBI core [7].

IV. CONCLUSIONS

We find that high levels of γ -ray activity in the quasars studied coincide with the production of new superluminal knots and their passage through stationary bright features in the jet, usually the mm-wave VLBI core. Therefore, in many blazars γ -ray outbursts occur parsecs downstream of the central engine, at or beyond the mm-wave core. This agrees with the need to avoid excessive opacity to pair production in blazars detected at TeV energies.

Acknowledgments

This research was supported by NASA grants NNX08AV65G, NNX08AV61G, NNX09AT99G, and NNX09AU10G, and NSF grant AST-0907893.

-
- [1] Abdo A.A. et al. 2010, *Nature*, 463, 919
 - [2] Abdo A.A. et al. 2010, *ApJ Letters*, 714, L73
 - [3] Agudo I. et al. 2011, *ApJ Letters*, 735, L10
 - [4] Foschini L. et al. 2011, 2011arXiv1110.4471F
 - [5] Jorstad S.G. et al. 2005, *AJ*, 130, 1418
 - [6] Jorstad S.G. et al. 2011, AAS Meeting #217, *Bulletin of the AAS*, 43, #408.04
 - [7] Jorstad S.G. et al. 2011, *Journal of Astrophysics &*

Astronomy, 32, 239

- [8] Lister M.L. et al. 2009, *ApJ Letters*, 696, 22
- [9] Marscher A.P. et al. 2008, *Nature*, 452, 966
- [10] Marscher A.P. et al. 2010, *ApJ Letters*, 710, L126
- [11] Tavecchio, F. et al. 2010, *MNRAS*, 405, 94
- [12] <http://www.bu.edu/blazars/VLBAproject.html>

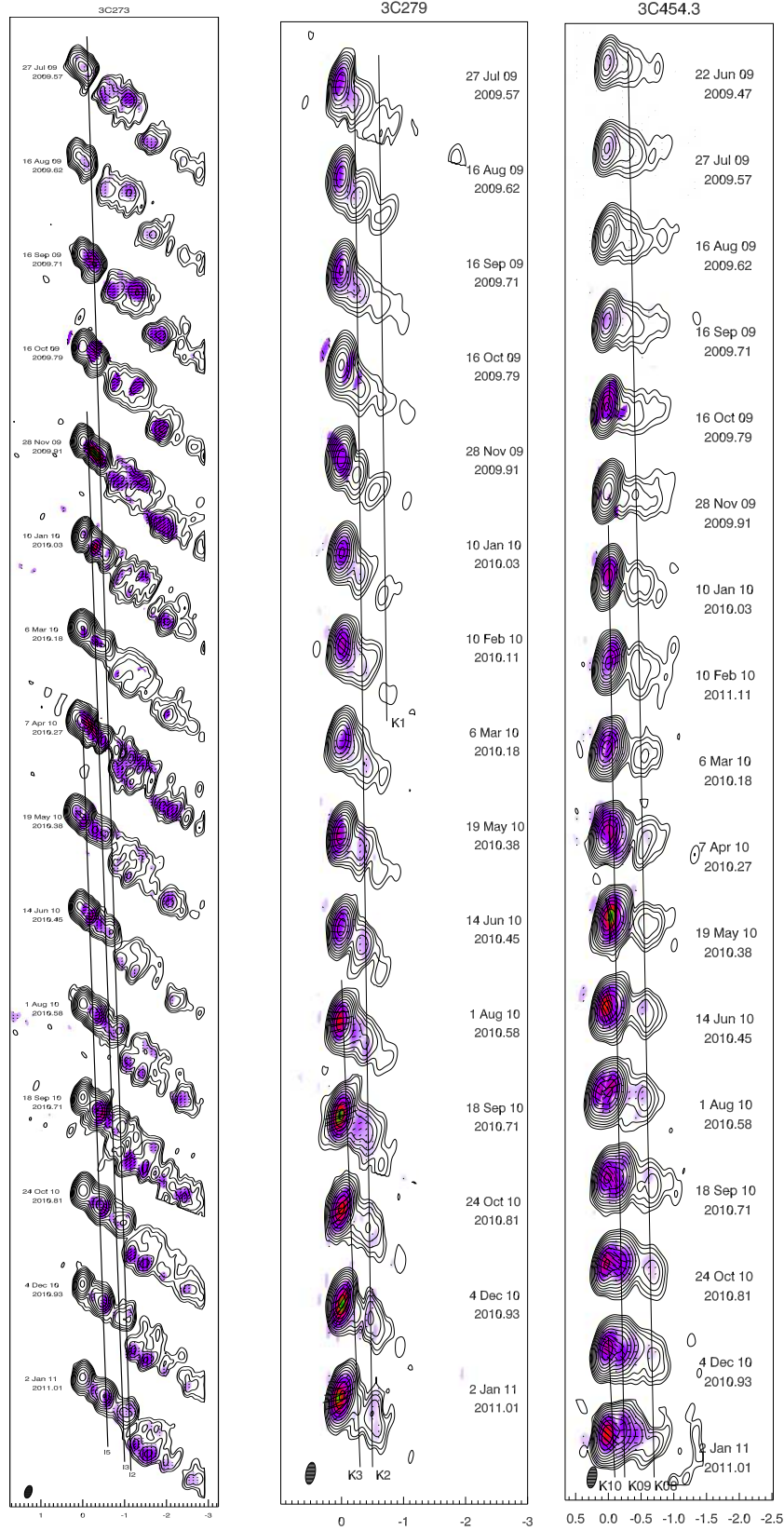


FIG. 1: Total (contours) and polarized (color scale) intensity images of the quasars 3C 273, 3C 279, and 3C 454.3; black line segments show direction of the polarization; the lowest contours are 0.25, 0.15, and 0.1% of the total intensity peak, $S_{peak}=10.0, 16.4$, and 20.3 Jy/beam, $S_{pol}=293, 955$, and 841 mJy/beam, respectively for 3C 273, 3C 279, and 3C 454.3.

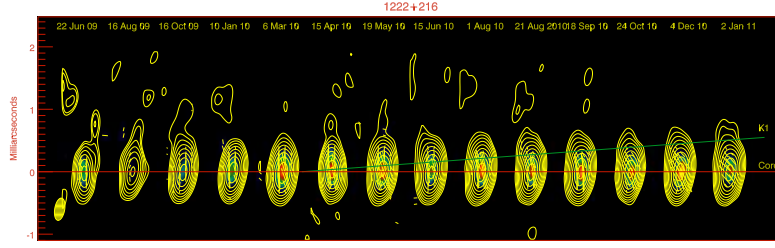


FIG. 2: Total (contours) and polarized (color scale) intensity images of the quasar 1222+216; yellow line segments show direction of the polarization; the lowest contours are 0.25% of the total intensity peak, $S_{peak}=1.68$ Jy/beam, and $S_{pol}=80$ mJy/beam.

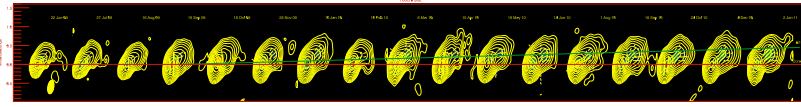


FIG. 3: Total (contours) and polarized (color scale) intensity images of the quasar 1633+382; yellow line segments show direction of the polarization; the lowest contours are 0.15% of the total intensity peak, $S_{peak}=2.64$ Jy/beam, and $S_{pol}=70$ mJy/beam.

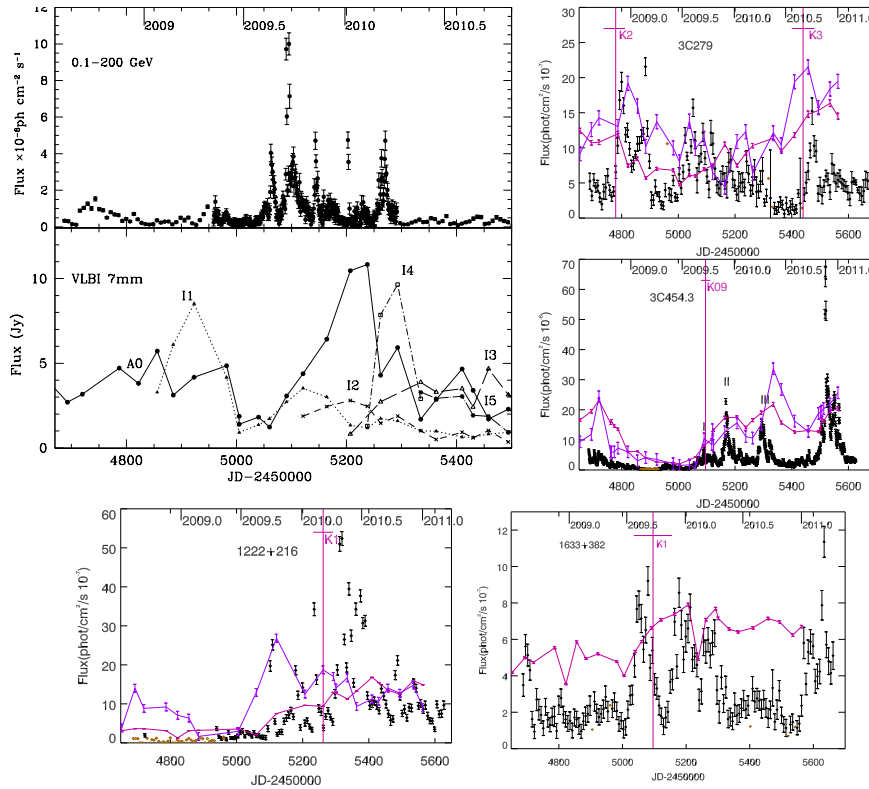


FIG. 4: *Upper Left*: γ -ray light curve (top panel) and light curves of the VLBI components (the second panel) for the quasar 3C 273. *Right & Bottom*: γ -ray light curves (black circles; brown circles upper limits) of 3C 279, 3C 454.3, 1222+216, and 1633+382, total intensity light curves of the VLBI core at 43 GHz (pink, in Jy, multiplied by factor of 3 for 1222+216 and 1633+382), fractional polarization curves of the core (violet), in %, multiplied by factor of 3; vertical pink lines show the time of passage of superluminal knots through the core.